

Process Industry Practices
Structural

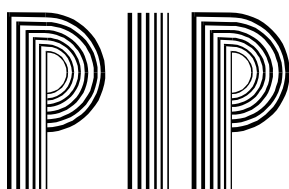
PIP STC01018
Blast Resistant Building Design Criteria

PURPOSE AND USE OF PROCESS INDUSTRY PRACTICES

In an effort to minimize the cost of process industry facilities, this Practice has been prepared from the technical requirements in the existing standards of major industrial users, contractors, or standards organizations. By harmonizing these technical requirements into a single set of Practices, administrative, application, and engineering costs to both the purchaser and the manufacturer should be reduced. While this Practice is expected to incorporate the majority of requirements of most users, individual applications may involve requirements that will be appended to and take precedence over this Practice. Determinations concerning fitness for purpose and particular matters or application of the Practice to particular project or engineering situations should not be made solely on information contained in these materials. The use of trade names from time to time should not be viewed as an expression of preference but rather recognized as normal usage in the trade. Other brands having the same specifications are equally correct and may be substituted for those named. All Practices or guidelines are intended to be consistent with applicable laws and regulations including OSHA requirements. To the extent these Practices or guidelines should conflict with OSHA or other applicable laws or regulations, such laws or regulations must be followed. Consult an appropriate professional before applying or acting on any material contained in or suggested by the Practice.

This Practice is subject to revision at any time by the responsible Function Team and will be reviewed every 5 years. This Practice will be revised, reaffirmed, or withdrawn. Information on whether this Practice has been revised may be found at <http://www.pip.org>.

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Appendix A Blast Design Requirements Data Sheet

Appendix B Commentary

1. Introduction

1.1 Purpose

The purpose of this Practice is to establish structural design criteria for new blast resistant buildings, including requirements for selection of structural systems, analysis methods, and design of ancillary items such as doors and openings.

1.2 Scope

This Practice also contains design criteria for non-structural items (architectural, electrical, HVAC, etc.) that may influence the design of blast resistant buildings.

2. References

Applicable requirements in the latest edition (or edition indicated) of the following codes, standards, and references shall be considered an integral part of this Practice. The edition in effect on the date of contract award shall be used, except as otherwise noted. Short titles will be used herein when appropriate.

2.1 Process Industry Practices (PIP)

- PIP CVS02010 - *Geotechnical Engineering Investigation Specification*
- PIP STC01015 - *Structural Design Criteria*
- PIP STC01018 – *Project Data Sheets*

2.2 Industry Codes and Standards

- American Concrete Institute (ACI)
 - ACI 318 - *Building Code Requirements for Structural Concrete*
 - ACI 530 - *Building Code Requirements for Masonry Structures*
- American Institute of Steel Construction (AISC)
 - *Load and Resistance Factor Design Specification for Structural Steel Buildings (LRFD)*
- American Iron and Steel Institute (AISI)
 - *Specification for the Design of Cold-Formed Steel Structural Members, Load and Resistance Factor Design, Cold-Formed Steel Design Manual, 1997.*
- American Society for Testing and Materials (ASTM)
 - ASTM A36 - *Standard Specification for Carbon Structural Steel*
 - ASTM A82 - *Standard Specification for Steel Wire, Plain, for Concrete Reinforcement*
 - ASTM A653 - *Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process*

- ASTM A514 - *Standard Specification for High-Yield-Strength, Quenched and Tempered Alloy Steel Plate, Suitable for Welding*
- ASTM A588 - *Standard Specification for High-Strength Low-Alloy Structural Steel with 50 ksi [345 MPa] Minimum Yield Point to 4 in. [100 mm] Thick*
- ASTM A615 - *Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement*
- ASTM A706 - *Standard Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement*
- ASTM C90 - *Standard Specification for Load-Bearing Concrete Masonry Units*
- International Conference of Building Officials (ICBO)
 - *Uniform Building Code (UBC)*, 1997 Edition

2.3 Other References

- ASCE - *Design of Blast Resistant Buildings in Petrochemical Facilities*, American Society of Civil Engineers (ASCE), 1997
- TM 5-1300 - *Structures to Resist the Effects of Accidental Explosions*, U.S. Dept. of the Army, 1990

3. Definitions

Angle of Incidence: The angle between the direction of the blast wave travel and a line perpendicular to the surface of a structure at the point of interest

Blast Loads: The transient dynamic loads from the blast effects of an explosion, usually stated in terms of peak pressure and impulse or duration

Conventional Loads: Loads applied in the conventional (non-blast) design of structures including dead, live, wind, and seismic loads as required by local building codes. These loads are typically statically applied.

DIF (Dynamic Increase Factor): A multiplier applied to the static strength of a material to reflect the increased effective strength due to fast strain rates caused by rapidly applied blast loads

Ductility Ratio: A measure of the degree of plasticity in a member at maximum dynamic response, equal to the maximum displacement divided by the displacement at yield. This value is a key measure of dynamic response.

Duration: The length of time from start of the initial positive phase of the blast pressure to the return to ambient pressure

Dynamic Reaction: The support reaction of a structural component to the dynamic blast loading, taking into account inertia effects

Engineer: The responsible professional in charge (Engineer-of-Record) of the blast resistant building design

Fragment Resistant: The resistance to high-speed fragments that result from the break up of equipment or structures that are close to the explosion source

Free-Field Pressure: The rise in above-ambient pressure produced by a blast wave sweeping unimpeded across a surface not facing the blast source. This is also referred to as side-on pressure.

Impulse: A measure used, along with the peak blast pressure, to define the ability of a blast wave to do damage. Impulse is calculated as the integrated area under the positive pressure vs. duration curve and is shown in units of MPa-msec (psi-msec).

MDOF (Multi-Degree of Freedom): Representation of a structure or component as a spring-mass system with more than one degree of freedom

Multi-Unit Building: The building used for support of multiple process units, where loss would adversely impact several separate process units

Negative Phase: The portion of the pressure-time history typically following the positive (overpressure) phase in which the pressure is below ambient pressure (suction)

Nonlinear Response: Deformation of a component or system beyond the elastic limit

Period: The fundamental natural period of a structural component when modeled as a single-degree-of-freedom (SDOF) system

Positive Phase: The portion of the pressure-time history in which the pressure is above ambient pressure

Rebound: The deformation in the direction opposing the initial blast pressure. This occurs after a component has reached a peak deformation and returns in the direction of its initial position.

Reflected Pressure (P_r): The rise in pressure above ambient produced by a shock wave or pressure wave striking a surface facing the direction of blast wave propagation

Response Range: The following descriptions apply to the response ranges mentioned in this Practice

Low (L) - Localized building/component damage. Building can be used; however repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.

Medium (M) - Widespread building/component damage. Building cannot be used until repaired. Total cost of repairs is significant.

High (H) - Building/component has lost structural integrity and may collapse from additional environmental loads (i.e., wind, snow, and rain). Total cost of repairs approach replacement cost of building.

SDOF (Single Degree of Freedom): Representation of a structure or component as a spring-mass system with one degree of freedom. Displacement of the SDOF system corresponds to the displacement of a single point in the real system, typically corresponding to the point of maximum deflection.

Side-On Pressure (P_{SO}): The rise in pressure above ambient produced by a blast wave sweeping unimpeded across any surface (walls or roof) not facing the blast source. This is also referred to as free-field or incident pressure.

SIF (Strength Increase Factor): A multiplier applied to the nominal strength properties of a material to reflect its actual strength above minimum specified values

Single-Unit Building: Building used for support/control of only one process unit

Support Rotation: The angle formed between the axis of a member loaded between its endpoints and a straight line between one endpoint and the point of maximum deflection. This value is a key measure of dynamic response.

4. General

4.1 Owner's Specific Data and Requirements

Data specific to each facility (building or project) to be used with this Practice shall be specified in the *PIP STC01018* Data Sheet (see Appendix A). The information that will be specified in the Data Sheet includes the following:

4.1.1 Blast Design Requirements

- 4.1.1.1 Building performance requirements and acceptable response range (low, medium, or high) (Refer to Section 6.4.3.)
- 4.1.1.2 Performance categories (I - IV) for blast resistant doors (Refer to Table 9.)
- 4.1.1.3 Blast loads specified as peak side-on positive pressure with corresponding impulse or duration at the building (See Section 5.3.)

4.2 Engineer's Responsibilities

- 4.2.1 Section 1.4 and Figure 1.1 of *ASCE (1997)* delineate information to be provided by the Owner and tasks to be performed by the Engineer. Items with overlapping responsibility in the flowchart will be the ultimate responsibility of the Engineer. The Engineer is responsible for producing a design, using sound engineering principles, that meets the requirements of this Practice.
- 4.2.2 The Engineer shall be responsible for designing the facility to meet the performance requirements specified in the Data Sheet. The Engineer shall bring any items requiring clarification to the Owner's attention.

4.3 Documentation

- 4.3.1 A Data Sheet will be prepared for each blast resistant building, by or on behalf of the Owner, and provided to the Engineer as a part of the job or project specifications.
- 4.3.2 The final design shall be prepared by the Engineer and shall include the following documentation:

4.3.2.1 *PIP STC01018* Data Sheet

4.3.2.2 Supporting calculations covering the design criteria, methodology, results, and the references and tools used

4.3.2.3 Detailed structural drawings and specifications for construction, as appropriate

5. Basic Requirements

5.1 Building Performance

The degree of structural damage permitted for blast resistant buildings, known as “building response range,” will be specified in the Data Sheet.

5.2 Building Configuration

Single-story construction shall be used where possible. Where multi-story construction is required, the number of stories shall be minimized and special design considerations shall be given to the inter-story response to the blast loading.

The floor plan and elevation preferably shall have clean rectangular profiles without re-entrant corners, and recessed areas shall be minimized.

5.3 Blast Loads

Each blast resistant building shall be designed for the dynamic blast loads provided in the Data Sheet. Blast loads on individual building surfaces shall be computed by the Engineer from the specified side-on pressure using the methods described in Chapter 3 of *ASCE (1997)*.

5.3.1 Component Loads

5.3.1.1 Structural components, doors, or appurtenance on an exterior surface of a blast resistant building shall be designed for the blast loading applicable to that surface. Specifically, each such component shall be designed for any one of the following:

5.3.1.1.1 The direct tributary blast load applicable to the surface of the building on which it is located

5.3.1.1.2 The dynamic reaction to the blast load on a supported component, as appropriate

5.3.1.1.3 The ultimate load capacity of the supported component

5.3.1.2 Where the blast effects on an appurtenance to the building are of little consequence, the building component must still be designed for the ultimate or “failure” load from such an appurtenance.

5.3.2 Foundation Load

The foundation for a blast resistant building shall be designed per Section 6.7 using any one of the following:

- 5.3.2.1 The peak dynamic reactions from the supported superstructure treated statically
- 5.3.2.2 The ultimate static capacity of the supported superstructure
- 5.3.2.3 The tributary area method. This method may be used in conjunction with the applied blast loads to determine foundation response using a dynamic analysis method.

5.4 Construction and Materials

The structural system and materials shall be selected to provide the most economical design that meets all performance requirements or as dictated by the Owner's specifications or architectural considerations.

5.4.1 Brittle Construction

Brittle construction, including unreinforced concrete, prestressed concrete, unreinforced masonry (block, brick, clay tile), poured gypsum, and cement-asbestos panels, shall not be used for load-carrying components of blast resistant buildings.

5.4.2 Advanced Materials

Advanced materials, such as composites, may be used if adequate test data are available to confirm their satisfactory performance for the intended application and if the Owner or Owner's Representative gives prior written approval. Such test data shall include the ultimate capacity and behavior of the material under dynamic conditions representative of blast loading. Satisfactory performance of the material under seismic condition is not sufficient to indicate blast capacity.

5.4.3 Fragment Resistance

Reinforced concrete or fully grouted reinforced masonry of appropriate strength and thickness shall be used as cladding where fragment resistance is required per the Data Sheet.

5.5 Material Properties

5.5.1 Dynamic Material Strength

- 5.5.1.1 Dynamic yield stress, F_{dy} , shall be computed as follows:

$$F_{dy} = F_y * SIF * DIF$$

F_y is the specified minimum static yield stress; DIF is the dynamic increase factor per Section 5.5.3; SIF is the strength increase factor per Section 5.5.2.

- 5.5.1.2 Dynamic design stress, F_{ds} , used to compute the dynamic capacity of structural components shall be based on the values listed in Tables 4 and 5 for structural steel and reinforcing steel, respectively.
- 5.5.1.3 Dynamic ultimate strength, F_{du} , shall be computed as follows:

$$F_{du} = F_u * DIF$$

F_u is the specified ultimate strength; DIF is the dynamic increase factor per Section 5.5.3.

5.5.2 Strength Increase Factor (SIF)

An SIF shall be applied to the specified minimum yield strength of structural materials to estimate the actual static value. The SIF shall be taken from Table 1 below.

Table 1. Strength Increase Factors for Structural Materials

Structural Material	SIF
Structural Steel with a Yield of 50 ksi (345 MPa) or Less	1.1
Concrete-Reinforcing Steel of Grade 60 (420 MPa)	1.1
Cold-Formed Steel Cladding Panels:	
- Yield Strength of 33 ksi (228 MPa) or Less	1.2
- Yield Strength of 50 ksi (345 MPa) or More	1.1
Concrete and Masonry	1.0
Other Materials	1.0

5.5.3 Dynamic Increase Factor (DIF)

To account for strain rate effects caused by rapidly applied blast loads, dynamic increase factors shall be applied to the static material yield and ultimate strengths to determine their dynamic values in accordance with Tables 2 and 3.

Table 2. Dynamic Increase Factors for Reinforced Concrete/Masonry

Stress Type	D I F			
	Reinforcing Bars		Concrete	Masonry
	(F_{dy}/F_y)	(F_{du}/F_u)	(f'_{dc}/f'_c)	(f'_{dm}/f'_m)
Flexure	1.17	1.05	1.19	1.19
Compression	1.10	1.00	1.12	1.12
Diagonal Tension	1.00	1.00	1.00	1.00
Direct Shear	1.10	1.00	1.10	1.00
Bond	1.17	1.05	1.00	1.00

Table 3. Dynamic Increase Factors for Steel and Aluminum

Material	D I F		
	Yield Stress		Ultimate Stress (F_{du}/F_u)
	Bending/ Shear (F_{dy}/F_y)	Tension/ Compression (F_{dy}/F_y)	
A36	1.29	1.19	1.10
A588	1.19	1.12	1.05
A514	1.09	1.05	1.00
A653	1.10	1.10	1.00
Stainless Steel Type 304	1.18	1.15	1.00
Aluminum, 6061-T6	1.02	1.00	1.00

Table 4. Dynamic Design Stress for Structural Steel

Type of Stress	Maximum Ductility Ratio	Dynamic Design Stress (F_{ds})
All	$\mu \leq 10$	F_{dy}
All	$\mu > 10$	$F_{dy} + (F_{du} - F_{dy}) / 4$

Note: μ = ductility ratio; F_{du} = dynamic ultimate strength; F_{dy} = dynamic yield stress

Table 5. Dynamic Design Stress for Concrete-Reinforcing Steel

Type of Stress	Type of Reinforcement	Maximum Support Rotation	Dynamic Design Stress (F_{ds})
Bending	Tension and Compression	$0 < \theta \leq 2$ $2 < \theta \leq 5$ $5 < \theta \leq 12$	F_{dy} $F_{dy} + (F_{du} - F_{dy})/4$ $(F_{dy} + F_{du})/2$
Direct Shear	Diagonal Bars		
Diagonal Tension	Stirrups		F_{dy}
Compression	Column	All	F_{dy}

where θ = support rotation (deg.)

6. Structural Design

6.1 Design Methods and Procedures

All blast resistant buildings and their structural components shall be designed using the methods provided in *ASCE (1997)*. Alternate design methods may be used with Owner's or Owner's Representative's prior written approval.

6.2 Load Combinations

6.2.1 In addition to the load combinations prescribed by *PIP STC01015*, a blast resistant structure shall be designed for the blast load condition as follows:

$$U(t) = D + aL + B(t)$$

where

$U(t)$ = total applied time dependent load or its effect

D = static dead load

$B(t)$ = time dependent blast load or its effect (horizontal and vertical)

L = conventional static live load

a = reduction factor applied to conventional live loads to reflect the portion of live load expected to occur simultaneously with the blast load. It shall be taken as zero if doing so will result in a more severe condition.

- 6.2.2 The blast load combination may consider either the direct loads or their effects. In combining blast load effects with those from static dead and live loads, the time dependence of the blast loading shall be taken into consideration.
- 6.2.3 Wind and seismic loads shall not be combined with blast loading.
- 6.2.4 Rebound effects shall be computed and combined with the effects of negative phase blast loads, if any, based on time dependent response.

6.3 Analysis Methods

The Engineer shall use analysis methods appropriate for the specific blast design. The selected methods shall adequately model the dynamic response of the structure to the applied blast loads and the structural component interaction. The analysis methods provided in Chapter 6 of *ASCE (1997)* shall be used, subject to the requirements below.

6.3.1 Single Degree of Freedom (SDOF)

The required resistance for each structural component shall be based on the peak blast pressure (or load) and duration, the natural period of the component, and the maximum allowable response (deformation). An SDOF analysis can be used where the connected components differ in natural period by a factor of 2 or more. The formulas and charts provided in Chapter 6 of *ASCE (1997)*, *TM5-1300*, or other similar references for the approximate solution of the elastic-plastic SDOF system may be used in determining the required resistance.

6.3.2 Multi-Degree of Freedom (MDOF)

MDOF analysis shall be used where the structural component interaction cannot be adequately modeled using the simpler equivalent static load or SDOF methods. The MDOF method may involve finite element analysis requiring the use of a special or general purpose structural analysis computer program with non-linear transient dynamic analysis capability.

6.4 Deformation Limits

6.4.1 Parameters

Structural members shall be designed on the basis of maximum response (deformation) consistent with the performance requirements or permissible damage level specified in Table B1. Deformation limits shall be expressed as ductility ratio (μ), support rotation (θ), or frame sidesway, as appropriate.

6.4.2 Building Response Range

The design response range or permissible damage level (low, medium, or high) shall be based on the building design requirements provided in Table B1.

6.4.3 Response Limits

Maximum response shall not exceed the limits specified in Tables 6, 7, and 8 for structural steel, reinforced concrete, and reinforced masonry, respectively.

Table 6. Deformation Limits for Structural Steel

Element Type	Response Range ⁽²⁾					
	Low		Medium		High	
	μ	θ	μ	θ	μ	θ
Beams, Girts, Purlins	3	2	10	6	20	12
Frame Members (1)	1.5	1	2	1.5	3	2
Single Sheet Metal Panels	1.75	1.25	3	2	6	4
Open-Web Joists	1	1	2	1.5	4	2
Plates	5	3	10	6	20	12

Notes:

(1) Sidesway limits for steel frames: low = $h/50$, medium = $h/35$, high = $h/25$.

(2) Response parameter: μ = ductility ratio, θ = support rotation (degrees).

Table 7. Deformation Limits for Reinforced Concrete

Element Type	Controlling Stress	Ductility Ratio, μ	Support Rotation $\theta^{(2)}$		
			Low	Medium	High
Beams	Flexure	N/A	1	2	4
	Shear: ⁽¹⁾				
	- Concrete Only	1.3			
	- Concrete + Stirrups	1.6			
	- Stirrups Only	3.0			
Slabs	Compression	1.3			
	Flexure	N/A	2	4	8
Beam-Columns	Shear ⁽¹⁾	1.3			
	Flexure	N/A	1	2	4
	Compression	1.3			
	Tension	(3)			
Shear Walls, Diaphragms	Shear ⁽¹⁾	1.3			
	Flexure	3	1	1.5	2
	Shear ⁽¹⁾	1.5			

Notes:

(1) Shear controls when shear resistance is less than 120% of flexural resistance.

(2) Stirrups are required for support rotations greater than 2 degrees.

(3) Ductility ratio = $0.05 / (\rho - \rho') < 10$, where ρ and ρ' are the tension and compression reinforcement ratios, respectively.

Table 8. Deformation Limits for Reinforced Masonry

Element Type	Ductility Ratio, μ	Support Rotation, θ (deg)		
		Low	Medium	High
One-Way	1	0.5	0.75	1
Two-Way	1	0.5	1	2

6.5 Component Design

6.5.1 General

Ultimate strength (limit state) methods shall be used for designing structural components for blast resistance. The ultimate strength capacity shall be determined in accordance with the applicable codes, practices, and guides specified in Section 2, subject to the following additional requirements:

6.5.1.1 In-plane and secondary bending stresses shall be accounted for in the design.

6.5.1.2 Interaction of forces in two directions, including biaxial bending, shall be considered as provided in the *ASCE (1997)*.

6.5.1.3 Dynamic strength properties shall be used to reflect increased material strength under rapidly applied loads.

- 6.5.1.4 Load and resistance factors shall be taken equal to 1.0 in all blast load combinations.
- 6.5.1.5 Composite sections may be used for design; however, adequate rebound resistance must be provided to ensure satisfactory response under rebound or negative phase loads.
- 6.5.1.6 Components shall be adequately laterally braced to prevent premature buckling failure during the positive and rebound response.
- 6.5.1.7 Connections shall be designed for 120% of the member's controlling resistance (flexure or shear, whichever is lower). Except as noted for reinforced concrete members, the deformation limits indicated in Tables 6, 7, and 8 are based on flexure-controlled resistance. To use these limits, the member's shear capacity shall be at least 120% of the flexural capacity.
- 6.5.1.8 Design for compression elements, such as load-bearing walls and columns, shall consider bending effects including p-delta and slenderness.

6.5.2 Reinforced Concrete

Reinforced concrete components shall be designed, using ultimate strength methods, in accordance with the provisions of *ACI 318* and *ASCE (1997)*. The following specific requirements shall also apply:

- 6.5.2.1 Deformation limits as noted for shear shall be used where the member's shear capacity is less than 120% of the flexural capacity.
- 6.5.2.2 Except as specified in the contract documents, a minimum 4000 psi (28 MPa) concrete compressive strength is recommended for the design of the concrete structures.
- 6.5.2.3 Reinforcing steel shall conform to *ASTM A706*, except that A615 Grade 60 (420 Mpa) may be used if the requirements of *ACI 318*, Section 21.2.5, are met. The maximum bar size shall be No. 10 (32 mm).
- 6.5.2.4 Wall and roof components shall be designed for in-plane and out-of-plane loads that act simultaneously by using the following equation:

$$[\Delta c / \Delta a]_i^2 + [\Delta c / \Delta a]_o^2 < 1.0$$

where

Δc = computed deformation (ductility ratio or support rotation)

Δa = allowable deformation

i = in-plane

o = out-of-plane

- 6.5.2.5 Slenderness effects shall be included for load-bearing walls and for members with significant axial loads.

- 6.5.2.6 Support shall be provided for roof slab to prevent failure during rebound. Headed studs may be used for this purpose; however, they shall be located and spaced to minimize composite action unless composite action is required and specifically designed for.

6.5.3 Structural Steel

Structural steel components shall be designed in accordance with the provisions of *AISC LRFD*, supplemented by the following requirements.

- 6.5.3.1 Materials with a specified yield strength of 50 ksi (345 MPa) or less shall be used for flexural design. Higher strength materials may be used where ductile behavior is not required.
- 6.5.3.2 Oversize holes shall not be used in connections that are part of the lateral force-resisting system.
- 6.5.3.3 Column base plates shall be designed to develop the peak member reactions applied as a static load. Dynamic material properties may be used for design of base plates.
- 6.5.3.4 Flexural members shall be laterally braced on both faces to provide consistent moment capacity in both positive and rebound response.

6.5.4 Cold-Formed Steel

Cold-formed steel components shall be designed in accordance with *AISI LRFD*, supplemented by the following specific requirements.

- 6.5.4.1 Ultimate resistance shall be determined using a factor of 0.9 applied to the plastic moment capacity.
- 6.5.4.2 Tensile membrane capacity of wall panels may be used if adequate anchorage of panel ends is provided.
- 6.5.4.3 Tensile membrane capacity of cold-formed girts and purlins may be utilized in the design if they are supported on the exterior face of a frame member and are continuous over three or more spans.
- 6.5.4.4 Oversize washers shall be provided for wall panel anchorage screws to prevent failure caused by rebound or negative phase loads.
- 6.5.4.5 Symmetric, closed sections shall be used wherever possible.

6.5.5 Open Web Steel Joist (OWSJ)

Design of OWSJ for blast loads may be accomplished using published load tables for static, working loads with appropriate factors applied to obtain the ultimate capacities with the following limitations:

- 6.5.5.1 A 10% reduction in ultimate moment capacity shall be used and is recommended unless special provisions are made to enhance ductility of the joist.
- 6.5.5.2 Lateral bracing shall be provided for the top and bottom chords as required to provide the necessary rebound resistance and positive moment capacity.

6.5.6 Reinforced Masonry

Design of reinforced masonry shall be in accordance with the ultimate strength method in *ACI 530*, *ACI 530.1*, and the *UBC* supplemented by the following specific requirements:

- 6.5.6.1 Hollow concrete masonry units (CMU) shall conform to *ASTM C90*, Grade N, with a minimum compressive strength (f_m) of 1500 psi (10.3 MPa).
- 6.5.6.2 All cells of hollow CMU shall be fully grouted.
- 6.5.6.3 Joint reinforcing shall meet the requirements of *ASTM A82* with a minimum yield stress of 70 ksi (483 MPa) and a minimum ultimate strength of 80 ksi (552 MPa).
- 6.5.6.4 Primary reinforcing bars shall conform to *ASTM A706* except that *ASTM A615* Grade 60 (420 MPa) may be used if the requirements of *ACI 318*, Section 21.2.5, are met.
- 6.5.6.5 Wall components subjected to in-plane and out-of-plane loads shall be designed using the interaction equation given in Section 6.5.2.5.

6.6 Structural-Framing Design

Design of the overall structural-framing system shall include analysis of global response including sidesway, overturning, and sliding. Sidesway analysis shall be performed with and without leeward side (rear wall) blast loads.

6.7 Foundation Design

Foundation design shall be based on a geotechnical report per *PIP CVS02010* and the geotechnical data summarized in the Section A-4 of *PIP STC01018* Data Sheet. Foundation components shall be designed per *ASCE (1997)* to resist the peak reactions produced by supported components resulting from the dead, live, and blast loads, treated either statically or dynamically, as noted below.

6.7.1 Static Analysis

Static application of the peak dynamic reactions from the wall and roof components may be used to design supporting members and to compute overturning and sliding effects. For blast load combinations, factors of safety for overturning shall be 1.2, and for sliding shall be 1.0.

6.7.2 Static Capacity

Foundations shall be designed using vertical and lateral soil capacities as follows:

- 6.7.2.1 Vertical - 80% of the ultimate net soil-bearing capacity for shallow foundations, including footings and mats. For piles and other deep foundations, 80% of the ultimate static capacities in compression and in tension may be used.
- 6.7.2.2 Lateral - Passive resistance of grade beams may be used to resist lateral loads if compacted fill is placed around the building

perimeter. Frictional resistance of spread footings and floor grade slabs shall be based on the coefficient of friction determined by the geotechnical study. The normal force shall be taken as the sum of the dead loads and the vertical load associated with the ultimate resistance of the roof. Frictional resistance of floating slabs shall not be used.

6.7.2.3 Where only passive resistance, frictional resistance, vertical piles, or battered piles are used to support the lateral blast loading, the resistance shall be taken as 80% of the ultimate static value. However, if two or more of these resistances are used to support the lateral blast loads, the lateral capacity shall be limited to 67% of the combined ultimate static resistance.

6.7.2.4 Foundation sliding may be permitted if it can be demonstrated that all underground and aboveground utility, electrical, and instrumentation lines entering and exiting the building have adequate flexibility to accommodate the slide.

6.7.3 Dynamic Analysis

To optimize the foundation design, its components may be analyzed dynamically for the calculated reaction-time history of the supported components. The required dynamic material properties of the foundation soils, including resistance and stiffness, shall be determined on the basis of an appropriate geotechnical investigation. No deformation limits are specified for dynamic response of foundations. The Engineer shall determine whether the predicted maximum response is acceptable for the permissible damage level of the building.

7. Ancillary Items

7.1 Blast Doors

Blast resistant doors shall be provided according to the following:

7.1.1 The performance category for the blast resistant doors shall be as specified in the Data Sheet. The response limits and other requirements shall be as given in Table 9.

Table 9. Blast Door Performance Requirements

Category	Door Condition after Blast	Panels	Ductility Limit	Edge Rotation (deg)	Door Function
I	Operable	Elastic	1.0	1.2	Primary Exit or Repeated Blasts
II	Operable	Significant Damage	3	2	Prevent Entrapment
III	Inoperable	Substantial Damage	10	8	Prevent Blast from Entering Building
IV	Inoperable	Failure in Rebound	20	12	Prevent Door from Becoming Debris Hazard

- 7.1.2 In buildings large enough to require more than one egress door as required by local building codes, at least two doors shall be designated as egress doors for the purpose of limiting the damage to these doors when subjected to blast loads. Designated egress doors shall not be located on the same side of the building.
- 7.1.3 Doors, door frames, and door hardware shall be designed for the performance criteria and applied blast loads specified in the Data Sheet.
- 7.1.4 Doors shall be outward opening and shall seat against the frame under the positive phase blast wave.
- 7.1.5 Blast door manufacturers shall provide calculations or test data to verify adequate blast resistance and door performance for the design load conditions.
- 7.1.6 Manually operated exit doors shall meet the requirements of the local building codes for the maximum opening force. Power-operated doors shall be used for exit doors that exceed the maximum opening force.
- 7.1.7 Reinforced conventional fire-rated metal doors may be used if substantiated with a design calculation or with test data to verify adequate blast resistance and door performance for the design load condition.

7.2 Windows

Windows normally shall not be used in blast resistant buildings. However, if windows are required, they shall be designed to provide protection under the applied blast load consistent with the overall building performance requirements specified by the Owner including the following requirements.

- 7.2.1 The design shall include the window frames and anchorage.

- 7.2.2 Acceptable products include properly designed laminated glass, tempered glass, and polycarbonates. Product performance shall be substantiated by test data.

7.3 Openings

Large openings in the building envelope, such as intake ducts, shall be designed to prevent entry of excessive blast pressures.

- 7.3.1 Blast valves, blast attenuators, or other devices shall be used to limit excessive blast pressure entry into the structure. Performance of the blast valve or attenuator shall be substantiated by test data and calculation.
- 7.3.2 Blast valves shall be provided for openings greater than 150 inch² (1000 cm²) in any surface in which the peak applied pressure is greater than 10 psi (0.07 MPa). Blast attenuators may be used for these openings if the peak applied pressure is greater than 5 psi (0.035 MPa).

7.4 Penetrations

- 7.4.1 Wall and roof penetrations in reinforced concrete and masonry shall be sleeved. Sleeves shall be anchored with a minimum of two (2) each 1/2-inch diameter x 4-inch (12-mm diameter x 100-mm) long headed studs.
- 7.4.2 Penetrations in metal-clad structures shall be anchored with substantial framing attached to structural steel members.

7.5 Suspended Items

Equipment and furnishings such as ceilings, HVAC ductwork, and light fixtures suspended from the roof inside the building shall be secured to structural framing members. Anchorage shall be designed to resist a statically applied force equal to the mass of the item times the maximum acceleration of the roof or five (5) times the weight of the item, whichever is less.

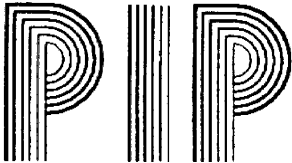
7.6 Externally Mounted Items

- 7.6.1 To avoid the potential for hazardous debris, large non-structural features such as canopies and signs on the building exterior should be minimized. However, small items such as instruments, fire alarms, lights, strobes, and beacons may be mounted on the exterior walls.
- 7.6.2 Roof- and wall-mounted equipment (e.g., HVAC equipment) should be avoided. If approved by Owner or Owner's Representative, such equipment shall be securely anchored and the supporting structural components shall be specifically designed for actual equipment dynamic loads when subjected to the blast.
- 7.6.3 Equipment and other items mounted on the exterior surfaces (walls or roof) of the building shall be designed similarly to the structural components if they are to withstand the applied blast loads. The reactions from such items shall be considered in the design of the supporting structural components.

7.7 Equipment and Internally Mounted Items

- 7.7.1 Instrumentation or electrical equipment shall not be mounted on the interior face of walls subjected to blast loads without Owner or Owner's Representative's prior written approval.
- 7.7.2 All fixed floor-supported items, such as lockers, electrical cabinets, racks, etc., shall have a minimum clearance from exterior walls equal to the maximum calculated lateral blast load deflection. The maximum deflection shall consider both the overall building sidesway plus deflection of any wall component(s) and shall be computed based on the maximum blast loads defined in the Data Sheet. Supports and anchorage for such equipment shall be designed to resist a lateral force equal to 20% of the equipment weight.

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	STC01018	DATA SHEET	APPENDIX A
		Blast Resistant Building Design Requirements	PAGE 1 OF 3 March 2001

Facility Name/Location: _____

Unit: _____ Job Number: _____

Building Name: _____ Building Number: _____

A-1. Blast Resistant Building Construction

A-1.1 Building Response Range: ☐ Low ☐ Medium ☐ High

A-1.2 Building Structural System:

(Check construction type from each column below. Provide details on back page if necessary.)

Frame	Wall	Roof
☐ Cast-In-Place Concrete	☐ Cast-In-Place Concrete	☐ Cast-In-Place Concrete
☐ Hot-Rolled Steel	☐ Precast Concrete	☐ Precast Concrete
☐ Pre-Engineered Metal	☐ Tilt-Up Concrete	☐ Single Sheet Metal Panel
☐ Load Bearing Wall	☐ Single Sheet Metal Panel	☐ Insulated Metal Sandwich Panel
	☐ Insulated Metal Sandwich Panel	☐ Insulated Metal Deck
	☐ Reinforced Masonry / CMU	☐ Composite Concrete Deck
☐ Other: _____	☐ Other: _____	☐ Other: _____

A-1.3. Fragment Resistant Required: ☐ Yes ☐ No

A-2. Blast Load Design Requirements

For each load case, the blast on each surface shall be determined using procedures provided in the ASCE (1997) (Chapter 3), based on the peak side-on pressure and corresponding durations or impulses as follows: (See Figure A1 on following page.)

Blast Load Parameters (1, 2, 3)

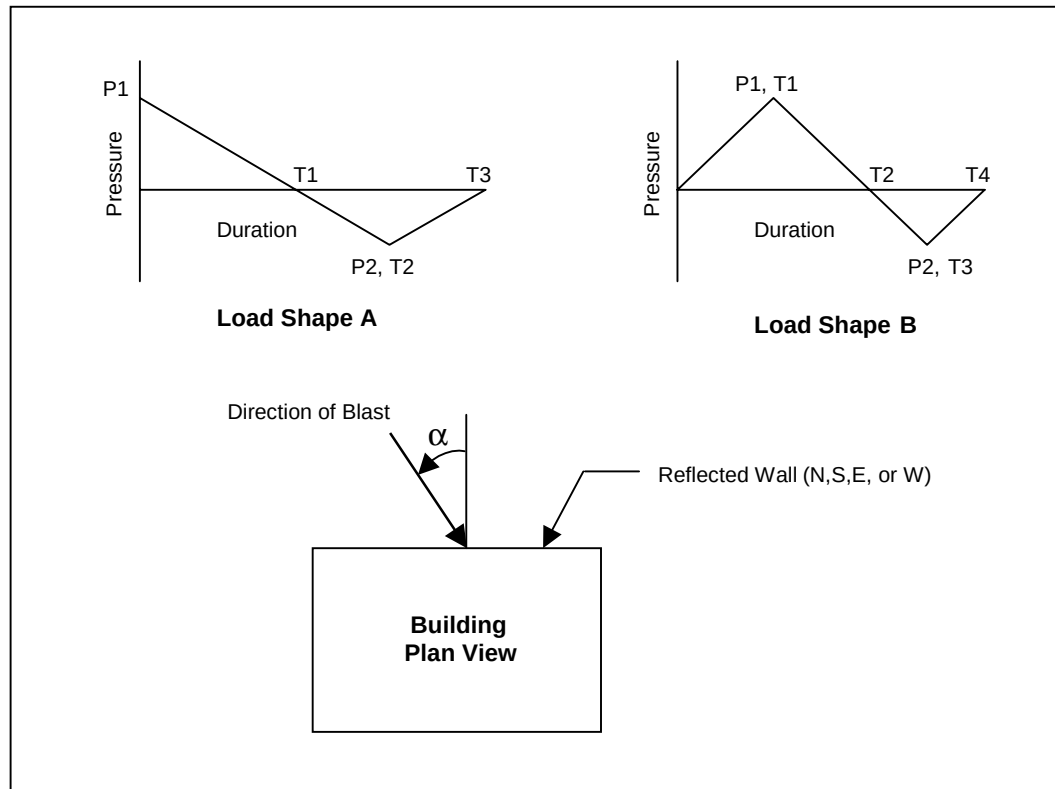
(4) Load Case	Description	Reflected Wall (4) (N, S, E, or W)	Load Shape and Angle A, B α (5)		Peak Side-On Pressure (6)		Duration msec			
					unit:		T1	T2	T3	T4
					P1	P2				

Notes:

- (1) Blast loads shall be computed at the wall nearest the blast center.
- (2) Roof shall be considered loaded by the peak side-on pressure.
- (3) Depending on the load shape, some of the parameters may not be applicable.
- (4) Each load case may see a different reflected wall. Indicate the wall (N, S, E, or W) facing the blast for the current load case.
- (5) Indicate angle of blast source (in degrees) measured from the line normal to the reflected wall.
- (6) Choose pressure unit from list (psi, MPa, millibar) or enter special unit name.

No.	Date	Description	By	Check.	App.

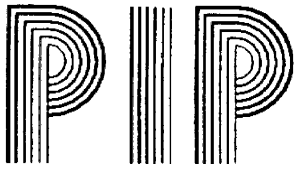
Figure A1 - Load Shapes and Building Orientation



A-3. Blast Door Requirements

The table below summarizes the design requirements for each blast door located in the exterior walls of blast resistant buildings.

[illegible]



STC01018

DATA SHEET

APPENDIX A

Blast Resistant Building Design
RequirementsPAGE 3 OF 3
March 2001**A-4. Geotechnical Requirements (Refer to *PIP CVS02010*)**

A-4.1. Foundation Type (Select one and provide data in the appropriate section.):

☐ Mat Foundation ☐ Spread Footing ☐ Pile Supported

A-4.2. Mat Foundation

Item	Value	Unit (*) / Special Unit	
Ultimate Net Bearing Capacity At Depth			psf (kN/m ²) ft (m)
Dynamic Modulus of Subgrade Reaction			pcf (kN/m ³)
Sliding Friction Coefficient			
Passive Pressure Coefficient			

A-4.3. Spread Footing Foundation

Ultimate Net Bearing Capacity At Depth			psf (kN/m ²) ft (m)
Sliding Friction Coefficient			
Passive Pressure Coefficient			

A-4.4. Pile-Supported Foundation

Pile Description			
Maximum Vertical Pile Capacity			kips (kN)
Maximum Horizontal Pile Capacity			kips (kN)
Vertical Pile Spring Constant			kips/in (kN/m)
Horizontal Pile Spring Constant			kips/in (kN/m)

(*) Note: Choose unit from list or enter user-defined name under Special Unit.

A-5. Other Special Requirements:☐ Blast Valves ☐ Blast Attenuators**Special Requirements:**

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APPENDIX B – COMMENTARY

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B-1 Introduction

B-1.1 Purpose

This recommended Practice focuses on the structural design of blast resistant buildings to be performed by a structural engineering professional (Engineer). It is expected that the requirements for the conventional and the non-structural (architectural, electrical, HVAC, etc.) designs of such buildings will be covered separately by the Owner.

This commentary to the recommended Practice provides additional information regarding the selection and application of the blast design requirements. The commentary is not a part of the design requirements but is intended to assist the Owner and Engineer in applying the criteria during the course of the design.

B-1.2 Scope

This recommended Practice is meant to cover new facilities when the Owner invokes it. It does not specifically address existing facilities; however, the methods discussed are applicable to analysis of existing buildings and the design of retrofits for such buildings. The Engineer should refer to the ASCE⁽¹⁾ for specific guidance on analysis of existing facilities.

Some buildings may not require design for blast for a variety of reasons, including negligible blast loads levels or non-essential functions, or they may not be occupied according to the Owner's occupancy criteria. The Owner should determine whether blast design is required for each facility and specify this in the project or job specifications.

A common issue related to design of structures at petrochemical facilities is the lower limit of overpressure below which blast resistant design is not required. Many companies have cutoffs ranging from 0.5 psi (3.4 kPa) to 1.0 psi (6.9 kPa) free-field overpressure. This load level will produce damage to conventional buildings, with damage ranging from cosmetic to moderate requiring repair for continued use.

The most rational approach is to design each building at a site for the predicted blast load developed in hazard analysis studies. However, this may not always be practical, in which case an acceptable lower bound overpressure level must be established for conventional construction below which blast design need not be considered.

Building occupancy may be used in determining the need for blast resistance in new or existing buildings. However, this recommended Practice does not cover occupancy criteria, which are addressed in other industry guidelines such as *API 752*⁽²⁾.

Application of this recommended Practice on blast design may be influenced by future plant or process unit development. A building may be at risk at some point in the future if a process unit is modified or if a new unit is added that can produce higher overpressures at a given structure. A master plan for facility siting is highly desirable to address this issue.

B-2 References

The Reference section of this Commentary lists the documents that are to be used with or referenced by this Practice. The recommended Practice is based primarily on the design methods and procedures provided in *ASCE*⁽¹⁾. However, other similar references and guidelines may be used. There are a number of other applicable references for design of blast resistant structures, including those developed for U.S. Department of Defense purposes. One of the most widely used of these references, *TM 5-1300*⁽³⁾, is also applicable to petrochemical facilities. However, the *ASCE*⁽¹⁾ is a “how to” document, which covers all aspects of blast design for buildings at petrochemical plants.

This Commentary lists additional references relevant to blast resistant design. Two of these are earlier petroleum industry blast design criteria/guides, *SG-22*⁽⁴⁾ and *CIA*⁽⁵⁾, which have been widely used for a number of years. These documents provide requirements for design of new facilities but are based on TNT-equivalent blast loads and the equivalent static load design method. They do not cover the more accurate design methods, the more complex forms of blast loads, or the structural design tools, which are now available and commonly used.

B-3 Definitions

The terminology used in this Practice is consistent with *ASCE*⁽¹⁾ and other blast design manuals such as *TM 5-1300*⁽³⁾ and *ASCE Manual 42*⁽⁶⁾. Some differences in definitions, especially for symbols, may exist in blast load prediction manuals. The Engineer should verify any conflicting definitions.

B-4 General

B-4.1 Owner-Specific Data and Requirements

In addition to the need for blast resistance, this Practice requires that the Owner provide certain data and requirements to the Engineer performing the design in the *PIP STC01018* Data Sheet. The Data Sheet is provided as Appendix A to this Practice.

B-4.2 Engineer's Responsibilities

The Engineer is responsible for designing a structure that provides protection in accordance with the response criteria based on the building performance requirements provided by the Owner or defined in this Practice. In situations for which a particular blast protection requirement is not covered in this Practice, conservative design assumptions should be made to ensure safety. The Owner should cover topics or issues not addressed. The Engineer should bring items requiring clarification to the Owner's attention as soon as possible to avoid project delays.

B-4.3 Documentation

The Data Sheet should completely describe the design criteria, blast loads, structural system, and ancillary equipment. Material and section properties should be tabulated to aid in future evaluation of alternate blast loads.

B-5 Basic Requirements

B-5.1 Building Performance

The required building performance is an important consideration by the Owner in establishing the building response range (permissible damage level) for a building under the design blast conditions. The building response range may be a function of many factors related to the acceptable risk for a given facility. A building response range must be selected, on the basis of the building performance required, and included in the Data Sheet. Such building performance requirements may be developed on the basis of the occupancy and function classification of the building as illustrated in Table B1.

Table B1. Building Performance Requirements

Building Classification	Example and Typical Performance Requirements	Building Response Range
Critical/Essential	Central control center, main electrical station. Continued use; reusable with cosmetic repairs	Low
Normally Occupied	Administration and engineering offices, laboratory. Damage-limited for occupant protection; not reusable without major repairs/replacement	Medium
Other	Operator shelters, warehouse. Collapse-limited; not repairable; abandon/replace	High

In some cases, greater damage to an existing facility may be tolerable than would be permitted for a new design, as it is normally much less costly to incorporate blast resistance into a new facility than to retrofit a structure to increase its blast capacity. The Owner should decide what philosophy is to be adopted in setting the response range for evaluating and retrofitting existing buildings for blast resistance.

B-5.2 Building Configuration

Blast resistant buildings should preferably be one-story construction with eave heights ranging up to 18 ft (5 m). Two-story construction may be required but should be used only when absolutely required. Two-story construction may be required where limited plot area prevents the layout of a single-story building. The floor plan for a building requiring blast resistance should be as simple as possible. A box type structure is preferable, in which the shorter side is exposed to the larger reflected blast load, and the longer side is exposed to the lower side-on blast load value. Roof

overhangs, canopies, and re-entrant corners should be avoided where possible to avoid additional blast wave reflections. Architectural items such as canopies and signs should be designed with light construction materials, such as canvas, to avoid creating a debris hazard for the structure.

B-5.3 Blast Loads

This recommended Practice does not cover development of explosion scenarios or prediction of blast loads, which therefore remain for the Owner to determine. Methods for blast load prediction and considerations for determining the design basis accident scenarios are provided^(6 to 10).

The Owner should specify the design blast load data in the Data Sheet (see Appendix A). As a minimum, the free-field overpressure at the building location should be provided. The Engineer may use the procedures provided in *ASCE*⁽¹⁾ to calculate the component blast loads on the basis of given free-field blast effects. The Owner may also provide more detailed information from a site-specific study, including the side-on or reflected pressure-time profile and orientation (angle of incidence) of the blast loading on each surface of the building. In this case, the Engineer should verify the location of the point of reference for the design blast loads. If sufficient information is available, including the location of the explosion reference point (epicenter) and the attenuation of the blast effects with distance from this point, variation of the blast load over the surfaces of the structure may be accounted for in the design.

Generally there are three approaches to specifying blast load for designing new facilities:

- 1. Using existing code/industry practice (default) values such as provided in SG-22⁽⁴⁾ and the UK CIA ⁽⁵⁾ Guide**
- 2. Establishing company generic values**
- 3. Basing the blast loads on site- or facility-specific explosion hazard studies**

In some situations, it is appropriate to develop site- and building-specific blast loads on the basis of potential explosion hazards from any existing, planned, or future facilities. Default or generic blast loads are not based on the specific site hazard but on certain standard conditions such as spacing, process unit size, and hazard level. In addition, if the building location is not determined or if sufficient process information and physical configuration of the process unit is not available, the blast loads can only be approximated. In these situations, generic blast loads may be appropriate. Such loads may be based on a building category or classification defined by its occupancy or function following a blast and the separation distance from a potential explosion hazard, as illustrated in Table B2.

Table B2. Building Classification Matrix

Building Classification Based on Blast Severity or Spacing	Separation Distance ft (m)	Pressure psi (kPa)	Impulse psi-ms (kPa-ms)	Building Performance Requirement & Damage Level (H, M, & L)		
				Damage Limiting	Collapse Limiting	Hazard Limiting
				I (L, M)	II (H)	III (N/A)
A						
B						
C						
D						

For reference, both SG-22⁽⁴⁾ and the CIA Guide⁽⁵⁾ specify two sets of blast loads for control buildings spaced 100 ft (30 m) to 200 ft (60 m) from a blast hazard (Building Class A-I, per Table B2). The first set is based on a side-on overpressure of 10 psi (69 kPa) for 20 msec, and the second on 3 psi (20.7 kPa) for 100 msec. The CIA Guide⁽⁵⁾ also specifies that such building should not collapse (that is, Class C-II) when subject to a worst-case blast load corresponding to 14.5 psi (100 kPa) side-on overpressure for 30 msec.

B-5.3.1 Component Loads

The blast load on each component of a building depends on the orientation of the building surface on which it is located. The following is a discussion of the blast loads for the main building components:

1. Wall Load

Normal reflection may be assumed without consideration of the angle of incidence of the blast wave. Clearing effects of the reflected blast wave may be accounted for by using the approach described in ASCE⁽¹⁾ or TM 5-1300⁽³⁾.

2. Roof Load

Roof load should be computed using the methods provided in ASCE⁽¹⁾, on the basis of the blast wave direction, component span, and spacing. For a flat roof (slope less than 20 degrees), roof load may be conservatively taken as the side-on value unless otherwise specified. For roofs sloped more than 20 degrees, the effects of blast wave reflection should be taken into consideration.

3. Side/Rear Wall Loads

The blast loads on the side walls and rear wall relative to the explosion source should be taken into consideration in the analysis

of the overall building. These loads may be computed using the methods given in Chapter 3 of *ASCE*⁽¹⁾ or may be conservatively assumed to be the side-on values.

4. Overall Building (Frame) Loads

The overall structural framing should be designed for net vertical and lateral blast loads acting on the building, taking into account the time phasing of these loads, as provided in *ASCE*⁽¹⁾.

The blast load on the rear face may be used to reduce the net lateral load for design of the overall structural framing system including diaphragm, shear walls, and foundation. The rear wall blast load may be ignored when this produces a more conservative design. However, if the rear wall loading is considered in the overall lateral blast loading, the lag time (delay in time of arrival) should be taken into consideration.

5. Negative Phase (Suction) Load

A negative phase load following the positive (overpressure) phase may be considered in the design if specified by the Owner. The effects of such a load should be considered in combination with the rebound effect from the direct blast pressure load.

B-5.4 Construction and Materials

A wide choice of construction types is available for blast resistant buildings, ranging from conventional construction to bunker-like concrete structures. The construction type is typically dictated by such factors as cost, blast load level, local practice, architectural considerations, and Owner preference. *ASCE*⁽¹⁾ (Chapter 4) describes some of the common types of construction used for blast resistant buildings in petrochemical plants.

Conventionally designed buildings can provide some level of protection against blast loads. The degree of protection provided depends on the ductility and redundancy of the structure. Ductile structures, such as metal frame/metal clad, can typically respond well into the plastic range and absorb blast energy. If connections are robust, components can develop tensile membrane action, which significantly increases their capability to resist load.

Table B3 lists some common types of building construction in the petrochemical industry, typical building function/use, the blast load ranges for each type of construction, and the tolerable damage level appropriate for the building function/use.

Table B3. Construction Type Matrix

Construction Type	Typical Building Function	Blast Load Range, Side-on Overpressure psi (kPa)	Tolerable Damage Level
Reinforced concrete	Central control room	High 7 (48) 10 (69)	Low
Precast concrete	Lab, office	Moderate - High 5 (35) 7 (48)	Low - Medium
Reinforced masonry	Office	Moderate 3 (21) 5 (35)	Medium
Metal frame, metal clad	Maintenance shop	Moderate - Low 2 (14) 3 (21)	Medium - High
Pre-engineered metal building	Warehouse	Low 1 (7) 2 (14)	High

B-5.4.1 General

Brittle structures, such as unreinforced masonry, have little ductility and will fail under very low blast loads. These failures are sudden and should be avoided in all situations. For this reason, unreinforced masonry construction is not permitted for design of blast resistant structures.

Redundant construction is also desirable for blast design. Redundancy is accomplished by providing alternate load paths and designing the structure to redistribute loads if a single component failure occurs. In metal frame buildings, where resistance to lateral loads is provided by girts and main frames, redundancy may be provided by strengthening the roof deck to act as a diaphragm and to distribute the load to other frames. Specific provision for redundancy is not required for design; however, redundancy should be provided where feasible and cost effective.

Metal frame, metal clad construction is commonly used in petrochemical plants for warehouses, maintenance shops, and process support office buildings. This type of construction is appropriate for relatively low blast overpressures and should typically be located several hundred feet from major process units.

Moment-resisting frames are typically used in a metal building to resist the lateral load applied on its long side. Cross bracing is used between frames to resist loads applied to the end or short walls of the building. However, the Engineer should be aware of special considerations for blast resistant design. Frame spacing must typically be closer, on the order of 20 ft (6 m), than for conventional construction, where frame spacing may exceed 30 ft (10 m). Heavier gage wall panels and closer girt spacing are typically required to develop any significant blast resistant capability. It may also be necessary to provide bracing for flexural members to develop a full plastic moment capacity for loads in both directions. This is a departure from typical construction, where bracing is normally required for a load in one direction only. Cladding fasteners should also be detailed to ensure proper resistance to rebound and negative phase blast loading.

Masonry buildings used for conventional construction can be classified as load bearing or non-load bearing. The response for the load-bearing construction is limited to ensure adequate safety against collapse under blast load. If a steel or concrete frame is provided, infill masonry walls can be allowed to achieve significantly more damage without risk of collapse. This non-load-bearing construction is preferred because it provides better redundancy and overall safety. Unreinforced masonry load-bearing construction may be adequate for relative low blast overpressures (< 1 psi (7 kPa)).

A metal deck may be used as a roof diaphragm for relatively low blast overpressures. A poured-in-place concrete deck is more typically used for masonry construction subjected to blast loads. It provides significantly more lateral capacity than does a metal roof deck. Anchorage for wall rebound must be provided. This will require a substantial bond beam at the top of the wall or secure ties into a concrete roof deck.

Precast concrete construction is widely used in petrochemical facilities for control rooms, plant offices, and process support buildings. Precast (non-prestressed) construction can be completed quickly and can provide significant blast resistance. The most significant consideration for blast resistant design is detailing of connections. Precast panels for conventional loads may have minimum blast capability because of the small number of connectors provided. For blast design, the number of connectors will be significantly increased and must be able to develop the full flexural capacity of the panel. When panel thickness is governed by architectural or mechanical considerations, the Engineer should ensure that connections are designed on the basis of the panel capacity rather than the required resistance for the blast.

Precast construction, like masonry, can utilize a load-bearing or non-load-bearing structural system. For load-bearing construction, detailing of connections to develop moment capacities is especially critical. The Engineer must also account for secondary bending effects, $P-\Delta$, caused by in-plane vertical loads. In non-load-bearing construction, steel frames are used to support the vertical loads and are recessed from the interior face of the wall panels to avoid applying lateral loads to the columns.

Cast-in-place reinforced concrete construction is typically used to provide resistance to severe blast loads. Wall thicknesses for structures in or immediately adjacent to large process areas are typically 8 inches (205 mm) to 12 inches (305 mm) but can be thicker for some special cases. Reinforced concrete is especially appropriate for short duration loading that produces an impulsive response. Its large mass, relative to the surface area, is especially effective in resisting these types of loads. Reinforced concrete construction is typically used where a protective structure is needed around an existing structure, when close to a blast source and thus must resist large blast loads.

B-5.4.3 Fragment Resistance

TM 5-1300⁽³⁾ contains design procedures for structures that are required by the Data Sheet to have fragment resistance.

B-5.5 Material Properties

B-5.5.1 Dynamic Material Strength

The dynamic design stress (F_{ds}) is used to compute blast capacity of a structural component. This design strength is constant throughout the response history and must therefore reflect an average value. Figure B1 illustrates the relationship of F_{ds} to F_{dy} and F_{du} . If the response is low, the portion of strength above yield is small to reflect the fact that the actual stress is nearly equal to F_{dy} for most of the response. If a large deformation is produced, the actual stress is closer to the dynamic ultimate strength (F_{du}). The tables provided in this recommended Practice show the design stresses to use for given levels of response. If the anticipated response is incorrect, a new design stress must be computed and new member properties determined.

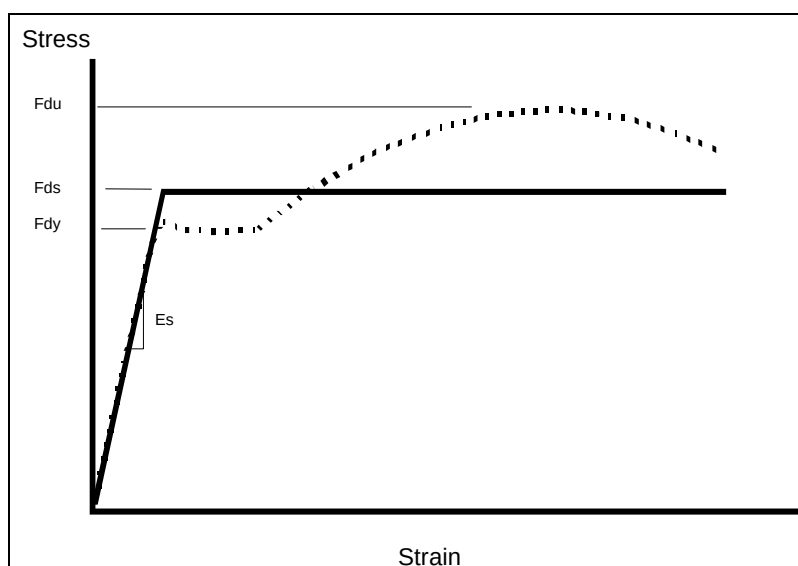


Figure B1. Yield, Ultimate, and Design Stresses

B-5.5.2 Strength Increase Factor

The strength increase factor (SIF) is used to reflect the fact that the actual yield and ultimate strength of a material is typically greater than the minimum specified value. Use of the SIF will produce more realistic member properties and will result in higher structural resistance. Failure to include the SIF will result in underestimating the member resistance and the resulting shear loads and dynamic reactions. This may not be conservative.

B-5.5.3 Dynamic Increase Factor

The dynamic increase factor (DIF) is used to account for the strain rate effects. Under blast-loading conditions, the material cannot respond as

quickly as the load is applied and an apparent strength increase is produced. Failure to include the DIF will also result in the under-prediction of member end shears and reactions. The strain rate can vary depending on whether the blast load is a pressure wave or a shock wave. A pressure wave may not produce strain rates sufficient to produce DIFs as high as shown in Table 2. *TM 5-1300*⁽³⁾ can be used for guidance on DIF values at relatively slow strain rates.

B-6 Structural Design

B-6.1 Design Methods and Procedures

An overall process involved in design of blast resistant structures in petrochemical facilities is shown in Figure B2 from ASCE⁽¹⁾. Most of the overlapping steps in the design process shown in Figure B2 will normally be the responsibility of the Engineer. If the Owner has specific requirements in these areas, they should be spelled out in the Data Sheet or the project/job design specifications. The Engineer should bring any unclear items to the attention of the Owner at the earliest possible time to avoid project delay.

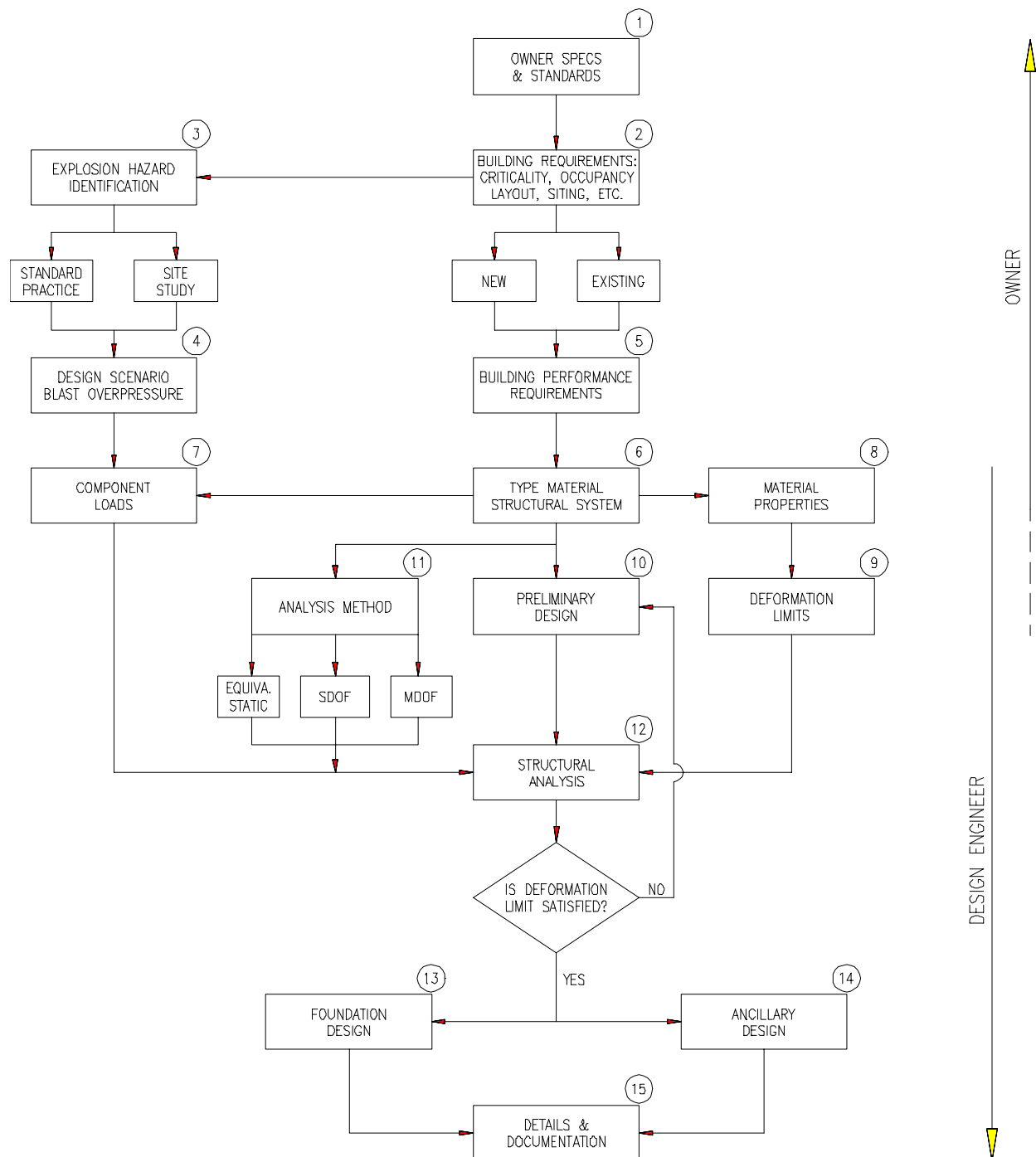


Figure B2. Overall Blast Resistant Design Process (from ASCE⁽¹⁾)

B-6.2 Load Combinations

Most design codes for conventional buildings have provisions for combination of design loads such as live, wind, seismic, snow, etc. For blast design, a decision must be made about which of these loads to include simultaneously with blast loads. Dead loads are always included, but most other transient live loads are not, although roof live loads (full or partial) are typically included.

The portion of live load to be applied in combination with blast load should be determined by the Engineer on the basis of the amount of load that could reasonably be expected to occur at the same time as the blast load. This would include snow loads, roof live loads, and floor loads. The full floor live load would not normally be used because of the low probability of blast occurring during application of the full floor live load. It is not normal practice to combine blast loads with extreme environmental loads such as wind or earthquake. In rare situations, it may be appropriate to analyze structural response for the blast load following application of seismic loads (for example, where an earthquake causes damage in a process unit, which leads to an explosion).

Most conventional design codes specify load factors to be applied to provide a factor of safety in the design. These load factors are typically set at 1.0 for blast design because a blast load is an extreme event.

B-6.3 Analysis Methods

B-6.3.1a SDOF - Approximate Solution (Equivalent Static Load)

This analysis method, which treats the required resistance as a static load, is based on the single degree of freedom (SDOF) response to a simplified blast load and may be used for components loaded directly by the blast.

This approach has been quite popular in the past because it is simple to apply. It is used to approximate dynamic response without requiring numerical integration of the equations of motion. *ASCE*⁽¹⁾ and *ASCE Manual 42*⁽⁶⁾ provide an empirical equation for computing the required resistance or equivalent static load for a component. These documents, as well as *TM 5-1300*,⁽³⁾ also provide plots of the response of an elastic-plastic SDOF system to a triangular shock load pulse. These represent approximate solutions for an elastic-perfectly-plastic SDOF system subjected to a linearly decaying blast load without a rise time.

Use of the equivalent static load method requires iteration. Initial properties for the member must be selected to define the period of vibration. When the static equivalent load is computed and applied, a new section is selected on the basis of computed resistance. This new section will have different properties than originally assumed, which will change the equivalent static load. If a new equivalent static load is not computed, subsequent calculations for member end shear and connection design will not be correct. This method does not directly calculate the dynamic shears and reactions of the member. The equivalent static load is used to determine these parameters, and in some cases may underestimate these items and thus the connection

requirements. Another drawback of this method is that it cannot model the interaction of connected components.

The equivalent static load method should be used only for analysis of a linearly decaying blast load without a negative phase. Furthermore, it should not be used for non-ideal resistance functions nor used to model differences in resistance for the positive response phase and the rebound phase.

B-6.3.1b SDOF - Numerical Integration

This is the most commonly used method for blast resistant design. This method allows most structural components to be modeled as a single, spring-mass system, which greatly simplifies the analysis of the time-history response. This method can be used to model non-linear resistance functions and the differences in resistance in the positive and rebound phases. It can also be used to model complex pressure-time histories including negative pressure effects. The time-varying end reactions can be computed using the SDOF method. These reactions can then be applied to supporting members to model component interaction. Special consideration needs to be given to selection of the appropriate mass to be applied to supporting members, based on the relative time to maximum response of the member being supported. Additional guidance is given in *ASCE*⁽¹⁾ and in References 11 and 12 for modeling and analyzing the response of structural components as SDOF systems.

Pressure-impulse (P-I) curves, denoting lines of constant damage corresponding to a particular response limit, may be used to evaluate the response of a structural component to a number of blast loads. This approach is described in *ASCE*⁽¹⁾ and in other References (7, 8, and 10).

B-6.3.2 MDOF

The multi-degree of freedom (MDOF) analysis method can be used to determine the dynamic response of interconnected members. Each component is modeled as a one-degree-of-freedom spring mass system. Several SDOF systems are combined numerically to produce a MDOF model. This method models mass and dynamic reaction effects on supported members. A typical system for a wall design might be modeled as a three-degrees-of-freedom system consisting of a wall panel, girt, and frame column. This type of analysis may result in a much lower maximum deflection than would a SDOF analysis if the periods of vibration of the connected members are fairly close.

The MDOF method can be used to model non-rigid (spring) supports, which may reduce the required resistance of certain components. A spreadsheet can be used to perform numerical integration of simple models consisting of two or three degrees of freedom. Beyond this, a computer program is more appropriate. There are a limited number of special purpose computer programs suitable for this type of analysis although most of these programs have been developed for defense-related applications. It is also possible to use a commercially available general purpose finite element program,

employing general spring elements to model and analyze non-linear MDOF systems subjected to transient blast loads.

Finite element analysis (FEA) is appropriate for analyzing a large system of components that cannot be accurately modeled using SDOF or MDOF methods. MDOF and FEA are essentially the same methods; however, FEA is usually distinguished as capable of modeling complex elements, whereas an MDOF method is based on equivalent spring elements. FEA is typically used to model response of a three-dimensional frame structure where biaxial bending and other three-dimensional effects are important.

A number of commercially available computer programs, referenced in *ASCE*⁽¹⁾, provide general finite element analysis capability and are capable of predicting dynamic response to transient loads. These programs are therefore suitable for blast resistant design. It is important to use a FEA program that is capable of accurately modeling non-linear effects, both material and geometric, and that can incorporate the effects of increased material strength under rapidly applied loads.

B-6.4 Deformation Limits

B-6.4.1 Response Parameters

For blast resistant design, the adequacy of the structural response is determined in terms of maximum deflection rather than stress level because the response typically will be in the plastic region of the stress-strain curve. It is normal practice to design blast resistant structures for plastic deformation when subjected to the extreme blast loads from accidental explosions. It is not cost effective to design such structures to remain elastic.

The two key parameters for evaluating structural response are support rotation (θ) and ductility ratio (μ). Support rotation is a function of the maximum deflection to span ratio. Figure B3 illustrates support rotation for a simple beam.

Ductility ratio is a measure of the degree of plastic response. A ductility ratio of 2 means that the maximum deflection is twice the deflection at the elastic limit. Steel members can achieve relatively high ductility ratios if buckling and shear modes of failure are prevented. The limits on deformation provide some conservatism for these effects.

Ductility ratio is an appropriate criterion for steel members, but it is a less reliable performance indicator for reinforced concrete components. Concrete members tend to be very stiff, which produces a very low elastic deflection. Thus, small dynamic deflections can produce large ductility ratios. Support rotation is a more reliable measure of performance for concrete or masonry.

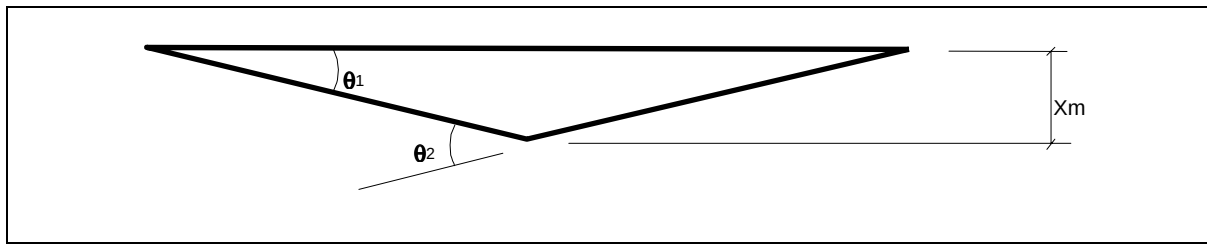


Figure B3. Definition of Support Rotation

θ_1 = Support rotation

θ_2 = Center hinge rotation = $2 \cdot \theta_1$

B-6.4.2 Building Response Range

The structural response or allowable damage level is set on the basis of the Owner-specified performance requirements for the building. The recommended response limits in this Practice corresponding to three damage levels (low, medium, high) are described in Table B4.

Table B4. Response Range Descriptions

Response Range	Damage Description
Low	Localized building/component damage. Building can be used; however repairs are required to restore integrity of structural envelope. Total cost of repairs is moderate.
Medium	Widespread building/component damage. Building cannot be used until repaired. Total cost of repairs is significant.
High	Building/component has lost structural integrity and may collapse because of environmental conditions (i.e. wind, snow, rain). Total cost of repairs approaches replacement cost of building.

B-6.5 Component Design

B-6.5.1 General

Structural components designed using SDOF analysis should include in-plane loads and secondary bending effects. These effects are typically incorporated as statically applied loads together with the flexural response to the transient loads.

Components must be designed to develop the full flexural capacity to avoid brittle failure modes. This type of response will provide the maximum blast-absorbing capability and will result in a controlled failure mode. This requires that components have sufficient shear and connection capacities. These required shear and connection capacities of a component are typically based on its full flexural resistance. Adequate bracing is also needed to prevent lateral buckling, which can result in sudden failures.

Short span components present a particular problem for developing flexural capacity. The primary response for these components is in shear, and thus it is not feasible in many cases to develop the full flexural capacity. In these

cases, the maximum resistance produced by the transient load should be determined for the entire response history. End shears and reactions should be based on 120% of the maximum attained resistance applied as a uniform load over the member.

B-6.5.2 Reinforced Concrete

Design of reinforced concrete should be to the ultimate strength method according to *ACI 318*⁽¹³⁾ or comparable concrete design methods. The customary strength reduction factor (ϕ) is to be taken as 1.0, and a dynamic stress factor (SIF * DIF) is applied according to Section 5.5.3 of this recommended Practice. In addition, because of the importance of adequate shear capacity to develop ductile flexural behavior in reinforced concrete components, the minimum static compressive strength for blast resistant design is set at 4,000 psi (28 Mpa). The higher strengths assure a more reliable performance in shear. However, a value less than 3,000 psi (21 Mpa) should not be used. A compressive strength of 5,000 psi (35 Mpa) is considered acceptable for concrete design. However, compressive strengths above this value have not yet had adequate testing to assure proper dynamic performance under blast load conditions.

Reinforcing steel higher than Grade 60 (420 Mpa) should not be used. In addition, bar sizes above a #10 (32 mm) should not be used because of decreased ductility for large bars. Use of a greater number of smaller bars is preferred to decrease development length requirements.

Time phasing of the interaction equation may be used; however, because of inaccuracies in load-time phasing and response, it is important to apply some conservatism to the design.

Prestressed concrete members should not be used. Prestressing strands have very limited ductility and may result in catastrophic collapse under application of blast loads at ultimate strength. In addition, prestressed components are typically designed for load application in one direction and do not provide adequate rebound resistance.

B-6.5.3 Structural Steel

The load and resistance factor design methods of *AISC*⁽¹⁴⁾ or comparable limit state methods may be used for the blast resistant design of structural steel. As in reinforced concrete design, $\phi = 1.0$ and the dynamic strength increase factors should be used. However, it is advisable to use/specify 50 ksi (345 Mpa) yield material because of the variation in material strength for A36 steel. Use of A36 material, which has an actual yield strength significantly more than 36 ksi, can lead to unconservative prediction of reaction forces and required shear resistance.

B-6.5.4 Cold-Formed Steel

The load and resistance factor design (LRFD) method of *AISI*⁽¹⁵⁾ or a comparable strength limit state method may be used for the blast resistant design of cold-formed steel members. A $\phi = 0.9$ factor is applied to plastic moment capacity when computing an ultimate resistance to reflect the

potential buckling of a section before developing the full plastic moment. In addition, the dynamic strength increase factors in Section 5.5.2 of this Practice should be applied.

B-6.5.5 Open Web Steel Joists (OWSJ)

OWSJ are not well suited for blast design because of difficulties in developing ultimate moment capacity. Web buckling can occur, especially at member ends, resulting in premature failure. Instability of the bottom chord during rebound can significantly reduce the rebound capacity. This potential problem can be remedied by supplying additional bracing to the bottom chord. When used, OWSJ should be designed on the basis of applicable standard specifications by the Steel Joist Institute⁽¹⁶⁾. Joist manufacturers' allowable load capacity tables may be used in determining the ultimate capacity of OWSJ under blast loading by multiplying the listed stress-based values by the applicable safety factor and by the appropriate dynamic strength increase factors.

Quality control in the manufacture of OWSJ can be an issue. Welding of bar joists does not typically comply with AWS D1.1⁽¹⁷⁾ and may not be capable of developing the plastic moment capacity of the joist. Because of these potential deficiencies in blast resistant designs, bar joists should be used with caution.

B-6.5.6 Reinforced Masonry

Only fully inspected reinforced masonry (concrete or brick) is appropriate for blast resistant design. The ACI⁽¹⁸⁾ and UBC⁽¹⁹⁾ specifications on the ultimate strength reinforced masonry should be used for blast resistant design, particularly those requirements pertaining to seismic design. ASCE⁽¹⁾ and TM 5-1300⁽³⁾ also provide guidance specific to the design of reinforced masonry for blast resistance.

Masonry construction responds similarly to singly reinforced concrete. Fully grouted cells normally provide adequate compression and shear capacity to develop flexural strength. Horizontal truss or ladder type reinforcing provides minimal flexural capacity and is not generally classified as reinforced masonry.

Connections at floor and roof are typically weak links in conventional reinforced masonry construction. The connections must be capable of resisting inward and rebound loads. Connections for load-bearing construction are especially critical. Walls should be doweled into floor and roof slabs.

B-6.6 Structural Framing

Analysis of frame sidesway should include analysis with and without blast overpressure on the leeward side of the building. Normally, excluding this load will produce the maximum response; however, in some situations the load applied to the leeward side may produce the maximum response when it occurs in phase with the rebound response. Accurate computation of time of arrival for the blast wave is important for this part of the analysis.

Dynamic analysis of sliding and overturning effects requires judgment on allowable deformations by the Engineer. Some guidance is provided in References 20 and 21. Vertical movement on the order of 1 inch (25 mm) is considered acceptable, while lateral movement as much as 2 inches (50 mm) may be acceptable. Using static methods, it is normally possible to show an adequate resistance to overturning and sliding. However, multi-story structures and buildings with a large aspect ratio floor plan may require dynamic analysis to show acceptable response.

ASCE⁽¹⁾, as well as other references (3, 11, 12), provides guidance in modeling and calculating the dynamic response of structural systems to blast loading.

B-6.7 Foundation Design

Analysis of explosion accident data has shown that foundation failure is rare. This is primarily due to the inability of the supported structure to transfer the entire blast load to the foundation. Additionally, foundation members are typically massive compared with superstructures and thus provide greater resistance to blast loads than does the supported building. Usually foundation components are simply designed statically for the capacities of the structural components they support. However, if this proves to be too conservative or costly, a more accurate dynamic analysis of the structure/foundation system can be performed as discussed above.

B-7 Ancillary Items

B-7.1 Blast Doors

The Owner should determine whether blast doors are required for the building. Blast doors are expensive, even for low blast loads, and may not be cost effective at low risk levels. Conventional hollow metal doors will not be operational above approximately 0.5 psi (3.4 kPa) applied peak pressure. If blast pressure entering a structure is not sufficient to cause damage, a conventional door may be acceptable.

Door hardware may not be required to remain operational if additional protected exits are provided. This situation may exist for doors on a wall receiving reflected loads. It may be appropriate to allow these doors to be substantially damaged if a sufficient number of doors are located in building faces receiving side-on blast loads. The Owner should select an allowable response category for design as shown in Appendix A. Additional information regarding door performance and design is provided in ASCE⁽¹⁾.

Support for blast door frames is very important. Typically, subframes are provided by the building contractor during wall construction. This allows construction to continue while blast doors are being fabricated, which may take several weeks or months. Door framing should be provided by the manufacturer.

B-7.2 Windows

Windows should be avoided in buildings subjected to significant blast loads. Laminated glass and polycarbonate glazing can provide substantial blast resistance; however, they require a large rebate, or bite, to prevent the glazing from pushing through the frame.

Reputable suppliers of blast resistant windows have test data available to substantiate performance. If windows are designed by the vendor, supporting calculations should be provided.

B-7.3 Openings

Small openings or low applied blast loads may not produce an appreciable increase in pressure in the building. In these situations, blast valves or other devices will not be required. For structures near a process unit, leakage pressures through air intake openings can be significant and valves or attenuators are required. *TM 5-1300*⁽³⁾ contains methods for predicting leakage pressure through openings.

Blast valves typically incorporate a moving disk that seals the opening and prevents entry of blast pressures. Blast attenuators significantly reduce leakage pressures but do not completely eliminate the blast.

Passive blast valves have no moving parts and reduce blast pressures by creating a tortuous exit path rather than a seal.

B-7.4 Penetrations

Premanufactured multi-cable transits (MCT) are available for use in blast resistant buildings. These devices have a frame that is anchored into the concrete or masonry. Flexible collars are placed around pipes running through the MCT and are clamped down to prevent leakage of the blast pressure into the structure. These MCTs are available in a variety of sizes.

B-7.5 Suspended Items

Light fixtures in suspended ceilings can produce a serious hazard to occupants during a blast. Ceiling grids, unless seismically rated, will not support fluorescent light ballasts and ventilation dampers. These items can be anchored to the roof framing with heavy gauge wire or threaded rod. Any item weighing more than 10 pounds (5 kg) should be independently anchored.

B-8 References

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